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# Efficiency in contamination-free machining using microfluidic structures

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## Abstract

The plastic deformation of the material in the chip formation and the friction when the chip slides on the rake face of the insert generate heat. The heat generation is responsible for a temperature rise of the chip, of the insert and of the newly created surface on the workpiece. Adhesion and diffusion between the chip and the insert are thus facilitated with detrimental effects on the tool wear. A cooling system based on microfluidic structures internal to the insert is considered in this study as a means of controlling the temperature at the chip-insert interface. The coolant and the part never enter in contact. Hence contamination of the part by coolant molecules is prevented. The aim of this study is to identify and to quantify the effect of the cutting parameters on the effectiveness of the internal cooling system. To measure this effectiveness an efficiency ratio  $r$  is defined as the percentage of the

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mechanical power actually needed at the tool to remove material that is thermally dissipated by the internal flow of the coolant. Similarly, a specific efficiency ratio  $r'$  is also defined by considering the mechanical power per volume flow rate of the material removed and the dissipated thermal power per volume flow rate of the coolant. Both  $r$  and  $r'$  are then analysed in a  $3^3$  factorial experiment within the space of the technological variables depth of cut, feed rate and cutting speed. The cutting trials were conducted in turning operations of AA6082-T6 aluminium alloy. Linear Mixed-effects models were fitted to the experimental results using the maximum likelihood method. The main finding was that the efficiency ratio  $r$  depends only on the feed rate and the cutting speed but not on the depth of cut. An interaction effect of the feed rate and the cutting speed on the efficiency was also found significant. Higher efficiency is attainable by decreasing cutting speed and feed rate. The maximum efficiency predicted in the technological region investigated was 10.96 %. The specific efficiency once log-transformed was found linearly increasing with the depth of cut and the feed rate, whereas being insensitive to the cutting speed.

*Keywords:* Cutting temperature, internally-cooled tool, contamination-free machining, dry machining, Linear mixed-effects statistical models

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## 1. Introduction

Dry cutting of key engineering materials is the epitome of sustainability in metal cutting. The removal of metal working fluids (MWF) from the machining processes is of benefit to the machine operator, swarf recycling and ultimately the environment. Reducing the temperature of the cutting tool

6 and workpiece is one of the main purposes of the MWF, together with facil-  
7 itating the removal of the chip from the machining area. Using an external  
8 supply of coolant makes it difficult for the fluid to penetrate into the tool-chip  
9 contact area. It is also difficult to quantify the amount of heat transferred be-  
10 tween the cutting edge and the MWF. Dry machining removes the externally  
11 supplied coolant from the machining process at the expense of the cooling  
12 effect it provides. Although this method is acceptable for certain materials  
13 like aluminium, it may be problematic for high strength materials and cer-  
14 tain grades of aluminium which contain harder elements like silicon. High  
15 temperatures which are uncontrolled due to lack of cooling can cause high  
16 wear rates and can dramatically reduce the useful life of the tooling insert.  
17 In some extreme cases the tool can become damaged not via traditional wear  
18 mechanisms but through deformation of the cutting edge [1]. Monitoring  
19 of the cutting temperature is a well-established research goal and has been  
20 presented using many differing technologies including an embedded thermo-  
21 couple [2], the tool-work thermocouple [3], the calorimetric method [4], an  
22 embedded sensor film [5] and optical methods [6, 7]. Some of these methods  
23 are not applicable when using an external coolant supply. Dry machining  
24 allows the monitoring of the tool/chip temperature via the tool-work ther-  
25 mocouple [3] or optical methods [6, 7]. These methods however require time  
26 consuming setups or expensive auxiliary equipment and are hence better  
27 suited to a laboratory environment.

28 The method of indirect cooling is known in the area of metal cutting and has  
29 been steadily increasing in popularity since 1970 when Jefferies published the  
30 idea of an internally cooled single-point cutting tool [8]. The main benefit

31 of the internally cooled tool is the indirect application of a cooling effect  
32 to the tool-chip interface. Previous research in the field of indirect cooling  
33 methods has shown that it is possible to reduce significantly the cutting tem-  
34 perature. In particular, Ferri *et al.* [9] compared the chip temperature in dry  
35 turning of the aluminium alloy AA6082-T6 when using conventional and in-  
36 ternally cooled tools. Their main finding was that the internally-cooled tools  
37 appeared increasingly effective in containing the chip temperature while in-  
38 creasing the depth of cut. In a research effort jointly sponsored by the US  
39 Environmental Protection Agency and the Department of the Army, Rozzi *et*  
40 *al.* [10] patented a device to cool indirectly the tool-chip interface by creat-  
41 ing micro-channels and a finned heat exchanger within the tool suitable for  
42 the use with cryogenic fluids (typically liquid Nitrogen). Sanchez *et al.* [11]  
43 proposed a similar apparatus where the cooling fluid flowing within the tool  
44 evaporates in proximity of the cutting edge, with the latent heat being pro-  
45 vided by heat transfer with the tool-chip interface. In a condenser outside  
46 the tool holder, the fluid is then condensed again. The resulting liquid phase  
47 is re-conveyed within the tool, thus realising a close-loop circulation of the  
48 coolant. Liang *et al.* [12] studied the use of the heat pipe technology in turn-  
49 ing operations. A heat pipe is a heat conductor in which the latent heat  
50 of evaporation is used for heat transfer purposes in experimental situations  
51 where differences in temperature are small. Moreover, a heat pipe operates  
52 without any external power supply. Shu *et al.* [13] presented a study based  
53 on the finite element method to simulate numerically turning operations in  
54 presence of both liquid coolant flowing in channels internal to the tool and a  
55 heat pipe. Uhlmann *et al.* [14] compared wet machining, dry machining and

56 machining with an internally-cooled tool. They investigated the influence  
57 of different coolant temperatures on the tool flank wear (VB) and on the  
58 workpiece surface roughness. Their main finding is that the tool wear in dry  
59 machining appears larger than in the other cases. They tested internally-  
60 cooled tools with coolant temperatures of 20 °C and -10 °C. The tool flank  
61 wear in both these cases and in the wet machining were most similar. The  
62 internally-cooled tool with coolant at 20 °C appeared only slightly less worn  
63 (cf. figure 3 in Uhlmann *et al.* [14]).

64 Moreover, internally cooling the tool also provides the unique possibility  
65 to manipulate the cutting temperature without necessarily changing core  
66 machining parameters such as the cutting speed, the feed rate or the depth  
67 of cut. Whilst specifically focusing on a closed loop coolant supply within  
68 the tool shank, the introduction of two additional control variables such as  
69 the coolant supply flow rate and the coolant temperature can be deployed to  
70 affect the metal removal process. The concept of a coolant supply within the  
71 cutting tool itself also presents a great opportunity to quantitatively assess  
72 the thermal energy that the coolant conveys away from the cutting zone. The  
73 metal cutting process generates high heat and large thermal gradients [3].  
74 According to Micheletti (cf page 203 in [15]), heat is almost instantaneously  
75 generated where work is done during cutting. Thus, the location of the heat  
76 sources is identified in the areas where the work due to the plastic deformation  
77 of the metal and to the friction of the chip on the rake face happen. If the  
78 tool is not in ideal conditions, i.e. if it is not perfectly sharpened, friction  
79 work also happens between the surface of the workpiece and the clearance  
80 face of the tool (also known as flank face) [15]. Boothroyd [16] measured the

81 temperature distribution and constructed isotherm patterns in the workpiece,  
82 the chip and the tool by making joint usage of infra-red photography and  
83 thermocouples. From those measurements, Boothroyd was also able to derive  
84 the heat transferred into the chip, the tool and the workpiece. Boothroyd's  
85 results, displayed in the table on page 797 in [16], appear consistent with  
86 those reported by Micheletti (cf page 209 in [15]): most of the heat generated  
87 during the cutting process is transferred into the chip, say about 60 and 80  
88 %, depending on the machining conditions; the remaining part is transferred  
89 into the tool and into the workpiece in similar proportions.

90 When the coolant flows internally to the insert and close to the cutting edge,  
91 a part of the generated heat is transferred into the coolant and away from the  
92 cutting zone. The heat transfer occurred is evidenced through the increment  
93 of the coolant temperature which is also instrumental to its measurement.  
94 This can all be achieved without the contamination of the tool and of the  
95 workpiece which instead occurs with external coolant supplies. For this rea-  
96 son the authors used in the title and elsewhere the terms 'contamination-free  
97 machining'. At first sight, this may appear as an oxymoron. In fact, for  
98 a metal cutting process to happen a tool must enter in contact with the  
99 workpiece. The cutting edge of the insert must be harder than the material  
100 to cut. Thus cutting edge and workpiece are of different materials. It is a  
101 reasonable expectation that during the cutting process a proportion of the  
102 material worn off the flank face (clearance face) of the tool will contaminate  
103 the workpiece at least on a sub-micrometre scale. Thus, strictly speaking, as  
104 long as flank wear exists on the tool, a cutting process is always most likely  
105 to pollute the workpiece with tool material. The term 'contamination-free'

106 is therefore to be considered within these limitations.

107 In some cases reducing the temperature of the workpiece or cutting insert  
108 by too great a margin might be a problem. For example, if there is a strong  
109 work-hardening effect on the material the cutting forces may increase dra-  
110 matically and induce additional issues with the surface finish and the surface  
111 integrity [17]. Another issue might be a thermal shock of the cutting insert.  
112 However, the manipulation of the coolant flow rate and/or the coolant tem-  
113 perature would make the management of these events possible. The benefits  
114 of a reduced cutting temperature appear to out-weigh the potential trou-  
115 bles by far. An increase in tool life is possible and a control of the critical  
116 temperature above which thermally induced wear mechanisms take place is  
117 achievable [18]. In this study, a tool system is designed and manufactured to  
118 cool the cutting insert by the adduction of the coolant in the proximity of the  
119 cutting insert via microfluidic structures within the tool. These structures  
120 prevent any possible contact between the coolant and the part. A cooling  
121 efficiency ratio is then defined and computed in a range of experimental con-  
122 ditions defined by the triplets of machining parameters cutting speed ( $v_c$ ),  
123 feed rate ( $f$ ) and depth of cut ( $a_p$ ). This efficiency ratio denotes the portion  
124 of the total machining power which is transferred to the coolant in the form of  
125 thermal power. From a conceptual point of view, establishing experimentally  
126 how this efficiency ratio depends on  $(a_p, f, v_c)$  provides other researchers a  
127 further potential means of validating their theories regarding the thermal  
128 characteristics of the machining process. From a practitioner's point of view,  
129 this efficiency ratio can become a useful instrument in the selection of the  
130 coolant flow rate and coolant temperature at the inlet of the tool system. For



131 example, cutting speed, feed rate and depth of cut may be set to comply with  
 132 productivity requirements and/or the optimisation of some cost function. By  
 133 setting the triplet  $(a_p, f, v_c)$ , the power request for machining a given ge-  
 134 ometry from a given blank is uniquely determined. The knowledge of the  
 135 efficiency ratio of the cooling system for the selected triplet  $(a_p, f, v_c)$  allows  
 136 then the practitioner to know how much thermal power would be transferred  
 137 away by the cooling system, had he or she set the flow rate and the inlet  
 138 temperature of the coolant to the same values of this investigation. Prior to  
 139 any actual machining, the efficiency ratio can therefore suggest to the prac-  
 140 titioner whether the flow rate and the inlet temperature of the coolant may  
 141 need increasing or decreasing in order to balance the mechanical power and  
 142 have a thermally steady machining condition. More in general, this study of  
 143 the efficiency ratio may constitute a stepping stone towards the formulation  
 144 of a performance objective function (e.g. cost, profit) to be optimised in the  
 145 newly established penta-dimensional technological space of depth of cut, feed  
 146 rate, cutting speed, coolant flow rate and coolant inlet temperature.

## 147 **2. Experimental set-up**

148 The tool has been assembled and secured to a dynamometer as shown in  
 149 Figure 1. The dynamometer was a three component Kistler type 9257B  
 150 which had been attached to the tool turret of an Alpha Colchester Harrison  
 151 600 Group CNC lathe.

152 [Figure 1 about here.]

153 The workpiece material chosen for this study was Aluminium 6082-T6 (0.7-  
154 1.3 % Si and 0.6-1.2 % Mg). This aluminium alloy is readily available and  
155 widely used in numerous applications, an additional benefit is the low me-  
156 chanical property demands on the tooling insert and therefore yields a low  
157 wear rate. A cylindrical workpiece of 65 mm diameter and 450 mm length  
158 was used. The internally cooled tool was enhanced in its measuring capabil-  
159 ity by mounting K-type thermocouples. These were installed within the inlet  
160 and the outlet pipes, close to where these pipes enter the tool body. These  
161 sensors measured the inlet/outlet coolant temperatures. They were linked to  
162 a PC via a National Instruments NI 9213 thermocouple input device. Data  
163 from the thermocouples and the dynamometer were collected and transferred  
164 to Labview prior to the analysis.

165 The internally cooled tool was comprised of the tool shank, a cooling adaptor  
166 and a hollow insert, as shown in Figure 1. The tool shank was an off the  
167 shelf model manufactured by Sandvik (CSBNR 2525M 12-4) which had been  
168 enhanced with designed fluid channels machined inside it. The adaptor block  
169 has been custom machined in mild steel. The cutting inserts were once  
170 again an off the shelf -item produced by Hertel (SNUN 120408, Tungsten  
171 Carbide WC with 6 % Cobalt). These were modified using electro discharge  
172 machining to create a hollow with a 1 mm wall thickness. The coolant was  
173 flowing from a central reservoir which contains approximately one litre of  
174 coolant. From here it flowed through silicone tubing to a micro-diaphragm  
175 pump from KNF-Neuberger (NFB 60 DCB). Upon exiting the pump, the  
176 coolant then flowed to and around the part of the circuit enclosed within the  
177 tool and finally back to the reservoir.

178 The volume flow rate of the coolant ( $Q$ ) was approximately 0.3 L/min for all  
 179 the tests, i.e. in SI units  $Q = 0.3/60\,000\text{ m}^3/\text{s}$ . The coolant was a 25 % in  
 180 volume liquid solution of Ethylene Glycol in water. The specific heat ( $C_p$ )  
 181 and the density ( $\rho$ ) of the coolant were considered essentially constant and  
 182 approximately equal to 3850 J/kg K and 1040 kg/m<sup>3</sup>, respectively. The  
 183 choice of using a 25 % Ethylene Glycol aqueous solution rather than water  
 184 was conservatively made to benefit from the ebullioscopic elevation of the  
 185 boiling point of the mixture. A bi-phase vapor-liquid flow within the inter-  
 186 nal microfluidics structures is in this way slightly less likely to take place.  
 187 This choice however adversely affects the efficiency of the cooling system.  
 188 For the same volume flow rate and for the same increment of temperature,  
 189 a coolant comprised of the Ethylene Glycol solution would exchange heating  
 190 power with the insert less than water would do. In the range of the tested ex-  
 191 perimental conditions, clean water has in fact comparable density but higher  
 192 specific heat than the mixture used (approximately  $\rho_{water} = 1000\text{ kg/m}^3$  and  
 193  $C_{p,water} = 4184\text{ J/kg K}$ , albeit they both are not constant).

### 194 **3. Design of the Experiment**

195 The temperature of the coolant at the inlet ( $T_{in}$ ) and at the outlet ( $T_{out}$ )  
 196 of the insert, together with the cutting and the thrust forces ( $F_c$  and  $F_t$ ,  
 197 respectively) were measured in a set of experimental conditions defined by  
 198 three technological variables: the depth of cut ( $a_p$ ), the feed rate ( $f$ ) and  
 199 the cutting speed ( $v_c$ ). These variables assume numerical values. They have  
 200 been therefore considered as continuous rather than categorical variables.

Each variable was assigned three values (Table 1). Thus a limited region was identified in the space  $(a_p, f, v_c)$ .

[Table 1 about here.]

Cutting trials were performed in the resulting  $3^3$  experimental conditions (treatments). In each treatment, the cutting test was replicated three times. thus the total number of tests accrued to 81. A unique label was given to each treatment. Then, a permutation of the 27 labels was randomly generated out of 27! possible label permutations. The treatments were run in the order defined by such a permutation. All the three cutting trials for a given treatment were performed in the same machine set-up. A full randomisation of the cutting tests would have requested a new machine set-up (different or equal to the latest) for each single cutting test. The set-up time of the machine made a full randomisation of the 81 tests impracticable.

#### 4. Modelling and Analysis

The thermal power exchanged between the coolant and the insert during machining ( $\dot{Q}$ ) causes the temperature of the coolant at the insert outlet ( $T_{out}$ ) to be higher than at the insert inlet ( $T_{in}$ , which is approximately equal to the ambient temperature). By the application of the first law of thermodynamics to the open system made of the coolant flowing in the microfluidic structures within the insert, the following equation is derived for the steady state:

$$\dot{Q} = Q \rho C_p (T_{out} - T_{in}) \quad (1)$$

221 From the measurements of the cutting force ( $F_c$ ) and the thrust force ( $F_t$ ), the  
 222 cutting power  $P_c = F_c (v_c/60)$  and the thrust power  $P_t = F_t (f/1000) (n/60)$   
 223 were calculated. In these expressions,  $n$  denotes the angular speed of the  
 224 blank in revolutions per minute, whereas the other coefficients have been  
 225 introduced to express the power in watt. To explore the relationship between  
 226 the efficiency of the internally-cooled tool and the machining conditions, a  
 227 definition of efficiency ratio  $r$  is introduced as follows:

$$r = 100 \frac{\dot{Q}}{P_c + P_t} \quad (2)$$

228 In equation (2), the efficiency ratio  $r$  represents the percentage of the power  
 229 needed to remove material from the blank that is thermally transferred by the  
 230 flow of the internal coolant. Alternatively,  $r$  can be described as the scaled  
 231 ratio of the heat transfer rate associated with the flow of the coolant and the  
 232 mechanical power used at the tool to remove material from the workpiece.  
 233 In other words, The coefficient  $r$  does not represent some measurement of  
 234 efficiency of the cutting process, but a measurement of efficiency of the in-  
 235 ternal cooling system. The idea behind this approach is that the internal  
 236 cooling apparatus is more efficient the more thermal power it can remove  
 237 from the system tool/chip/workpiece per unit of power in input to such a  
 238 system, regardless of how this input power is then distributed between the  
 239 workpiece, the chip and the tool. In this view, the efficiency of a machine  
 240 tool in converting electrical power into mechanical power available at the tool  
 241 is also not relevant.

242 A specific efficiency ratio  $r'$  is also introduced as follows:

$$P_s = \frac{P_c + P_t}{(a_p/1000) (f/1000) (v_c/60)} \quad (3)$$

$$r' = 100 \frac{\dot{Q}/Q}{P_s} \quad (4)$$

243 The numerical coefficients in Equation (3) were introduced to convert the  
 244 measured technological variables to the SI units (m, m/rev and m/s). In  
 245 equation (4), the ratio  $r'$  represents the percentage of the total machining  
 246 power per unit of volume ( $\text{m}^3$ ) of material removed from the blank in the unit  
 247 of time (s) that is thermally dissipated by a unit of volume flow rate ( $\text{m}^3/\text{s}$ )  
 248 of the coolant. Both the dimensionless ratios  $r$  and  $r'$  have been considered  
 249 as two response variables separately analysed. The measuring procedure for  
 250  $r$  and  $r'$  is the same for all the treatments.

251 Improving the efficiency merit by increasing the coolant mass flow rate ( $\dot{m} =$   
 252  $Q\rho$ ), by identifying more efficient coolant fluids (with higher  $C_p$ ), by refrig-  
 253 erating the coolant (i.e. reducing  $T_{in}$  in Equation (1)) are all actions that  
 254 can be thought of, but that were not within the scope of this study. Hence  
 255 such actions were not taken. For example, the usage of cryogenic media such  
 256 as nitrogen and carbon dioxide has been reported in other cooling systems  
 257 such as high pressure jet cooling systems (cf page 311 – 338 in [19]). Op-  
 258 posite to the internally-cooled tool presented in this investigation, in those  
 259 systems the cryogenic coolant is a consumable: it evaporates rather than  
 260 being re-circulated in a closed-loop.

261 The parameters involved in the construction of a statistical model may  
 262 have desirable statistical proprieties if the independent variables are centred  
 263 around zero. Typically, intercepts and slopes are more likely to be uncorre-  
 264 lated if the independent variables are centred (cf. for example Pinheiro and  
 265 Bates [20], page 34). Also, dimensionless independent variables facilitate the

transformation of the data, which is often necessary in the construction of a model. For these reasons, dimensionless, centred, independent variables were defined as follows:

$$a'_p = 100 \frac{a_p - 0.35}{0.35}; \quad f' = 100 \frac{f - 0.15}{0.15}; \quad v'_c = 100 \frac{v_c - 300}{300} \quad (5)$$

The equations (5) define the per cent deviations from the central point  $(a_{p,c}, f_c, v_{c,c}) = (0.35 \text{ mm}, 0.15 \text{ mm/rev}, 300 \text{ m/min})$ , which is the centre of the investigated region in the space of the technological variables.

[Figure 2 about here.]

The diagram of the ratio  $r$  versus  $a'_p$ ,  $f'$  and  $v'_c$  is displayed in Figure 2. The abscissae of the data have been increased by a random amount to avoid overlapping points and thus increasing the readability of the figure (a procedure called jittering). In the same figure the sample mean of the data for each value of the pertinent independent variable has been designated by a cross. A qualitative visual analysis of Figure 2 raises the suspicion that the dimensionless depth of cut  $a'_p$  does not significantly affect the efficiency ratio  $r$ , whereas the dimensionless feed rate  $f'$  and the dimensionless cutting speed  $v'_c$  may do. When either  $f'$  or  $v'_c$  increases the efficiency ratio  $r$  appears to deteriorate. Also, the variability of  $r$  may be significantly inflated at high  $a'_p$ , low  $f'$  and low  $v'_c$ . Interaction plots (not shown here for brevity) were also constructed but they did not exhibit any pattern either strongly pointing to or strongly ruling out any significant second order interaction.

Running the experiment in 27 experimental units (alias blocks), each coincident with a treatment, suggests introducing a random effect in the model

288 to account for physical events or circumstances that may lurk within an ex-  
 289 perimental unit while the tests are performed. For example, the portion of  
 290 the blank being machined in an experimental unit may have micro-structural  
 291 and mechanical proprieties slightly different from those of other experimental  
 292 units. Without the introduction of a random effect, the likely effect of these  
 293 properties on the measured response would then be unduly attributed in part  
 294 to the independent variables.

295 A preliminary tentative model of the experimental data is as follows:

$$r_{ijkl} = \beta_0 + \beta_1 a'_{p,i} + \beta_2 f'_j + \beta_3 v'_{c,k} + \beta_4 a'_{p,i} f'_j + \beta_5 a'_{p,i} v'_{c,k} + \beta_6 f'_j v'_{c,k} + \beta_7 a'_{p,i} f'_j v'_{c,k} + b_{ijk} + \varepsilon_{ijkl} \quad (6)$$

296 where the subscripts  $i = 1, \dots, 3$ ,  $j = 1, \dots, 3$ ,  $k = 1, \dots, 3$  and  $l = 1, \dots, 3$   
 297 represent the different depths, feed rates, cutting speeds and replications  
 298 of the tests, respectively. The  $\beta$ 's are eight unknown parameters of the  
 299 model,  $b_{ijk}$ 's are the 27 non-observable random variables associated with the  
 300 corresponding experimental units,  $\varepsilon_{ijkl}$  are the 81 non-observable random  
 301 variables that model the random error. It is then assumed that all the random  
 302 variables in equation (6) are independent, identically distributed and normal  
 303 with constant variance, namely:  $b_{ijk} \sim N(0, \sigma_b^2)$ ,  $\varepsilon_{ijkl} \sim N(0, \sigma^2)$ , where  
 304 the standard deviations  $\sigma_b$  and  $\sigma$  are two further unknown parameters of the  
 305 model. Under these assumptions, the ten model parameters are estimated  
 306 using the maximum likelihood method (ML) as implemented in the library  
 307 **nlme** [21, 20] of R, a free language and run-time environment for statistical  
 308 computing and graphics [22]. The significance of the terms associated to the  
 309 technological variables that enter Equation (6) by the  $\beta$ 's has been tested  
 310 sequentially in the order they appear in the model and conditionally on the



311 estimate of  $\sigma_b$  (cf. Pinheiro and Bates [20], 89-92). A term is added in the  
 312 model only if such an inclusion reduces significantly the variability of the  
 313 predicted errors. The test was performed using the `anova()` function of the  
 314 `nlme` library.

315 [Table 2 about here.]

316 The results of the tests displayed in Table 2 support the conclusion that  
 317 Equation 6 does not fit the data any better than the following simpler model  
 318 equation, which is thus to be preferred:

$$r_{ijkl} = \beta_0 + \beta_2 f'_j + \beta_3 v'_{c,k} + b_{ijk} + \beta_6 f'_j v'_{c,k} + \varepsilon_{ijkl} \quad (7)$$

319 The library `nlme` allows the experimenters to predict the observed response  
 320 values by the fitted model, both at population level, i.e.  $\hat{E}[r_{ijkl}] = \hat{E}[r_{ij}] =$   
 321  $\hat{\beta}_0 + \hat{\beta}_2 f'_j + \hat{\beta}_3 v'_{c,k} + \hat{\beta}_6 f'_j v'_{c,k}$  and at experimental unit level, i.e.  $\tilde{E}[r_{ijkl}|b_{ijk}] =$   
 322  $\tilde{E}[r_{ijk}|b_{ijk}] = \hat{\beta}_0 + \hat{\beta}_2 f'_j + \hat{\beta}_3 v'_{c,k} + \hat{\beta}_6 f'_j v'_{c,k} + \tilde{b}_{ijk}$  (with  $E[X]$  designating  
 323 the expected value of  $X$ ,  $\hat{\alpha}$  the estimate of the parameter  $\alpha$  and  $\tilde{X}$ , the  
 324 predictor of the random variable  $X$ ). In this second case, the best linear  
 325 unbiased predictors  $\tilde{b}_{ijk}$  of the random effects are also calculated (*BLUES*,  
 326 cf. Pinheiro and Bates [20], 94). In turn, predictions of the non-observable  
 327 errors can thus be computed and are usually referred to as residuals, namely:  
 328  $\tilde{\varepsilon}_{ijkl} = r_{ijkl} - \tilde{E}[r_{ijkl}|b_{ijk}]$ . Departures from the hypotheses underlying the  
 329 model are diagnosed by the graphical analysis of the residuals.

330 [Figure 3 about here.]

331 In part (a) of Figure 3 the dispersion of the residuals around the zero appears  
 332 to increase with the values fitted by the model of Equation (7). Such an

333 observation is inconsistent with the assumed equal variance of the errors ( $\sigma^2$ ).  
 334 To overcome the violation of this hypothesis, the response is logarithmically  
 335 transformed in the following new model:

$$\log(r_{ijkl}) = \beta_0 + \beta_2 f'_j + \beta_3 v'_{c,k} + \beta_6 f'_j v'_{c,k} + b_{ijk} + \varepsilon_{ijkl} \quad (8)$$

336 An equivalent representation of equation (8) is given by its multiplicative  
 337 form:

$$r_{ijkl} = e^{\beta_0} e^{\beta_2 f'_j} e^{\beta_3 v'_{c,k}} e^{\beta_6 f'_j v'_{c,k}} e^{b_{ijk}} e^{\varepsilon_{ijkl}} \quad (9)$$

338 More details regarding suitable transformations of the response to overcome  
 339 observed departures of the assumed homoscedasticity of the errors in the  
 340 case of linear models are presented by Faraway (cf pages 53–58 in [23]). The  
 341 parameters in Equation (8) and (9) have been estimated as in the previous  
 342 cases using the `nlme` library (Table 3). The adequacy of the fitted model has  
 343 been assessed with the Akaike Information Criterion ( $AIC$ ), formally defined  
 344 by  $AIC = -2 \log \text{Lik} + 2 n_{par}$ , where  $\log \text{Lik} = 29.70$  is the log-Likelihood of  
 345 the fitted model (i.e. the maximum log-Likelihood) and  $n_{par} = 6$  is the num-  
 346 ber of parameters estimated in the model, thus  $AIC = -47.39$  (cf Pinheiro  
 347 and Bates [20], pages 10, 83, 84).

348 [Table 3 about here.]

349 In part (b) of Figure 3 the residuals of the model involving the log-transformed  
 350 efficiency ratio  $r$  appear to have a dispersion around zero that is markedly  
 351 less dependant on the fitted values than in the original model with untrans-  
 352 formed response (part (a) of Figure 3). Also, two residuals labelled ‘66 a’  
 353 and ‘66 c’ in part (b) of the same figure are noticeably lying quite far apart

354 from the majority of the others. The two labels indicate that these two resid-  
 355 uals have been obtained as the first and third replicate of the treatment 66,  
 356 which corresponds to  $a_p = 0.5$  mm,  $f = 0.1$  mm/rev and  $v_c = 300$  m/min  
 357 ( $a'_p = 42.86$ ,  $f' = -33.34$ ,  $v'_c = 0$ ). No specific reason has been identified  
 358 for the two associated experimental results to cause this outlying situation.  
 359 Thus there was no reason for excluding the two experimental results from  
 360 the analysis. Moreover, even doing so, the resulting fitted model did not lead  
 361 to significantly different estimates of the parameters. Namely, the confidence  
 362 intervals for corresponding parameters in the two models were overlapping.  
 363 The fact that these two residuals were obtained in the same experimental  
 364 unit instils the suspicion that the uncontrollable unknown reason causing  
 365 the outlying of the two residuals may be related to the specific experimental  
 366 unit. In this sense, the two outlying residuals reinforce the motivations for  
 367 introducing the random effects  $b_{ijk}$  in the model of the experimental results.  
 368 Without random effects as in the following model equation:

$$\log(r_{jk}) = \beta_0 + \beta_2 f'_j + \beta_3 v'_{c,k} + \beta_6 f'_j v'_{c,k} + \varepsilon_{jk} \quad (10)$$

369 the residuals appear inconsistent with the assumption of errors ( $\varepsilon_{ijkl}$ ) char-  
 370 acterised by zero mean and equal variance.

371 [Figure 4 about here.]

372 In Figure 4, when the random effects  $b_{ijk}$  are part of the model (cf. part (a)  
 373 of the figure), the three residuals corresponding to each experimental condi-  
 374 tion (treatment) have a sample mean that is close to zero. Otherwise, they  
 375 have not (cf. part (b) of the figure). The deviation of such a sample mean  
 376 from zero is what the random effect of a treatment is specifically meant to

377 account for. Moreover, in part (b) of the figure, 15 of these sample means  
 378 are negative, whereas 12 are positive. This symmetry in the distribution of  
 379 the realised random effects is consistent with the assumed normality of the  
 380 random effects. Q-Q plots have also been constructed and did not contradict  
 381 dramatically the assumed normality of both residuals and random effects for  
 382 the model of Equation (8). The figures were not included for sake of brevity.  
 383 In addition, in Figure 4 the dispersion of the realised residuals around their  
 384 mean is visibly smaller when the random effects are included in the model  
 385 (part (a) of the figure). All these qualitative observations have been substan-  
 386 tiated by testing the hypothesis  $\sigma_b = 0$ . Under the not-disproved assumption  
 387 of normality of both random effects and errors, a likelihood ratio test was  
 388 conducted using a Monte Carlo approach. A short script was implemented  
 389 in R to obtain an empirical distribution of the test statistics. 50 000 realisa-  
 390 tions of the test statistics were simulated in pseudo-random numerical tests.  
 391 The p-value obtained was less than 0.00002 and led therefore to reject the  
 392 hypothesis  $\sigma_b = 0$ .

393 The values of the specific efficiency ratio  $r'$  versus the dimensionless techno-  
 394 logical variables  $a'_p$ ,  $f'$  and  $v'_c$  are displayed in Figure 5. From the observation  
 395 of this figure, there is some strong suspicion that the specific efficiency ra-  
 396 tio  $r'$  increases substantially with the dimensionless depth of cut. Possibly,  
 397 also increments of the dimensionless feed rate may moderately improve  $r'$ ,  
 398 whereas the dimensionless speed of cut appears as hardly having any effect  
 399 on  $r'$ . In Figure 5 it can also be noticed that increasing the dimensionless  
 400 depth of cut  $a'_p$  appears to inflate the dispersion of the  $r'$  values around their  
 401  $a'_p$  mean.

402

[Figure 5 about here.]

403

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405

A quantitative analysis confirmed these initial intuitions. By following the same methods and procedures as in the case of the efficiency ratio  $r$ , Such an analysis ultimately led to the following model equation:

$$\log(r'_{ijkl}) = \beta_0 + \beta_1 a'_{p,i} + \beta_2 f'_j + b_{ijk} + \varepsilon_{ijkl} \quad (11)$$

406

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The ML estimates of the parameters for the model in Equation (11) are displayed in Table 4. The corresponding  $AIC$  is -45.28, the maximum log-Likelihood is 27.64 and  $n_{par} = 5$ .

409

[Table 4 about here.]

410

## 5. Discussion

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The fixed effects part of the model of Equation (8) and (9) allows predictions to be made regarding the typical efficiency ratio  $\hat{E}[r_{ijkl}]$  when the technological variables are set within the experimental region investigated. Figure 6 provides an operational graphical representation of this model to assist its interpretation.

416

[Figure 6 about here.]

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In such a figure, the yellow or light-grey transparent area respectively in colour and black-and-white print represents the region of the technological parameters experimentally explored. For any dimensionless feed rate in that area, increasing the cutting speed deteriorates the expected efficiency  $r$ . The maximum expected efficiency ratio in the area is 10.96 % and is obtained

422 at the minimum feed rate and minimum cutting speed investigated (point  
 423 A, at the corner of the yellow/light-grey region in Figure 6). The variable  
 424  $v'_c$  enters the model with a coefficient that is approximately the double in  
 425 absolute value of that associated with  $f'$  ( $\hat{\beta}_3/\hat{\beta}_2 \cong 2$ ). This supports the  
 426 idea that the efficiency ratio  $r$  is more sensitive to per cent variations in  
 427 cutting speed rather than in feed rate. The positive interaction coefficient  
 428 ( $\hat{\beta}_6$ ) is about one fifth of that of  $f'$  and one tenth of that of  $v'_c$  (both taken  
 429 in absolute value). Hence for positive  $f'$  the degree of sensitivity of the  
 430 expected efficiency ratio  $r$  to  $v'_c$  is slightly less than what implied by  $\hat{\beta}_3$   
 431 alone. In the experimental region investigated, however, this sensitivity to  
 432  $v'_c$  is always larger than that to  $f'$ . When both  $f'$  and  $v'_c$  are positive or  
 433 both are negative, the increment in efficiency ratio obtained by reducing  
 434 both  $f'$  and  $v'_c$  is less than the sum of the increments that can be obtained  
 435 by reducing  $f'$  and  $v'_c$  separately. The situation is reversed when  $f'$  and  
 436  $v'_c$  are of opposite sign. Any statement based on the extrapolation of the  
 437 model outside of the experimental region investigated needs per se further  
 438 experimental campaigns to be substantiated. However, an examination of  
 439 the behaviour of the model outside the region investigated experimentally  
 440 (the yellow/light-grey highlighted area in Figure 6) may assist the planning  
 441 of future experiments. In Figure 6, it is observed that when considering  
 442  $f' < -33.333$  the sensitivity of the expected efficiency to the cutting speed  
 443 is increased greatly. When instead  $33.333 < f' < 62.798$ , increments in  
 444 cutting speed still decrease the efficiency, but less and less. The value  $\bar{f}' =$   
 445  $-\hat{\beta}_3/\hat{\beta}_6 = 62.798$  is where any  $v'_c$  is expected to be equally efficient, namely  
 446  $\bar{r} = e^{\hat{\beta}_0 - \frac{\hat{\beta}_2 \hat{\beta}_3}{\hat{\beta}_6}} = 5.1122$ . For values  $f' > 62.798$  the expected efficiency ratio

447  $r$  is increasing and no longer decreasing with  $v'_c$ . The effect of  $v'_c$  on the  
448 efficiency ratio is reversed because of the interaction term in the model. The  
449 point B in Figure 6 is the stationary saddle point of the model.

450 The above analysis indicates that in the investigated area and likely in large  
451 areas beyond it (up to  $f' < 62.798$ ), the cooling system is more efficient, the  
452 smaller the cutting speed and the feed rate are. Hence, the cooling system  
453 is more efficient the smaller the mechanical power needed for the machining  
454 operation is. A decrease in machining power is accompanied with a less than  
455 proportional decrease in power dissipated by the cooling system.

456 Opposite to the case of the efficiency ratio  $r$ , the expected values of the  
457 specific efficiency ratio  $r'$  synthesised in Equation (11) do not exhibit any  
458 dependence on the cutting speed  $v'_c$ . They do however display a dependence  
459 on the depth of cut  $a'_p$  which does not exist for the ratio  $r$ . In contrast  
460 with the ratio  $r$ , the log-transformed specific efficiency  $r'$  does appear to be  
461 linear in the significant independent variables. Otherwise stated, there is no  
462 significant interaction between the two independent variables.

463 The model of Equation (11) shows that a unit volume flow rate of coolant  
464 dissipates more thermal power out of the mechanical power needed to gener-  
465 ate a unit volume flow rate of chip when the depth of cut and the feed rate  
466 are larger. This conclusion seems consistent with the intuition that when  
467 the contact tool-workpiece is larger the thermal exchange between workpiece  
468 and tool is facilitated. Therefore more power can be dissipated into the tool  
469 and then into the cooling system. Large depths of cut and large feed rates  
470 increase the theoretical cross section of the chip (i.e. the cross section prior to

471 actual removal of the chip from the part). So therefore they do increase the  
472 contact region tool-workpiece. The expected specific efficiency  $r'$  is sensitive  
473 to variations of depth of cut approximately twice as much it is to variations  
474 of feed rate ( $\hat{\beta}_1/\hat{\beta}_2 \cong 2$ ). Whereas the depth of cut does not have any signif-  
475 icant effect on the efficiency  $r$ , increasing it appears to improve the specific  
476 efficiency  $r'$ .

## 477 6. Conclusions

478 Microfluidic structures internal to the tool have been designed and manufac-  
479 tured to convey the flow of coolant in the near proximity of the cutter edge.  
480 The part and the coolant never enter in contact. Contamination of the part  
481 by molecules of the coolant is thus prevented.

482 The designed and manufactured internally-cooled tool system enabled heat  
483 transfer from the cutting zone of the insert to the flow of the liquid coolant.  
484 Measurements of cutting force, thrust force, coolant temperature at the inlet  
485 and at the outlet of the tool system were taken in a  $3^3$  experimental conditions  
486 defined by the depth of cut, the feed rate and the cutting speed. Each  
487 condition was replicated three times.

488 An efficiency ratio  $r$  and a specific efficiency ratio  $r'$  were respectively defined  
489 as the percentage of the whole machining power that is transferred to the  
490 coolant and as the percentage of machining power per volumetric flow rate  
491 of material removed that is transferred to a unit volume flow rate of the  
492 coolant.



493 Linear mixed-effects statistical models were fitted to the experimental results  
 494 using the maximum likelihood method. The analysis revealed that the effi-  
 495 ciency ratio  $r$  depends exponentially on the cutting speed and on the feed  
 496 rate, whereas it does not depend on the depth of cut. Within the investi-  
 497 gated experimental region, the less the cutting speed and the feed rate are,  
 498 the higher the expected efficiency ratios  $r$  are. The maximum expected effi-  
 499 ciency is therefore obtained at  $f_{min} = 0.10$  mm/rev and  $v_{c,min} = 250$  m/min  
 500 and is equal to 10.96 %. A significant interaction effect of cutting speed and  
 501 feed rate on the efficiency ratio  $r$  was also identified. The specific efficiency  
 502 ratio  $r'$  was instead found exponentially depending on the depth of cut and  
 503 the feed rate with no significant interaction effect. In other words, the  $\log(r')$   
 504 was found to be linearly increasing with the depth of cut and the feed rate.

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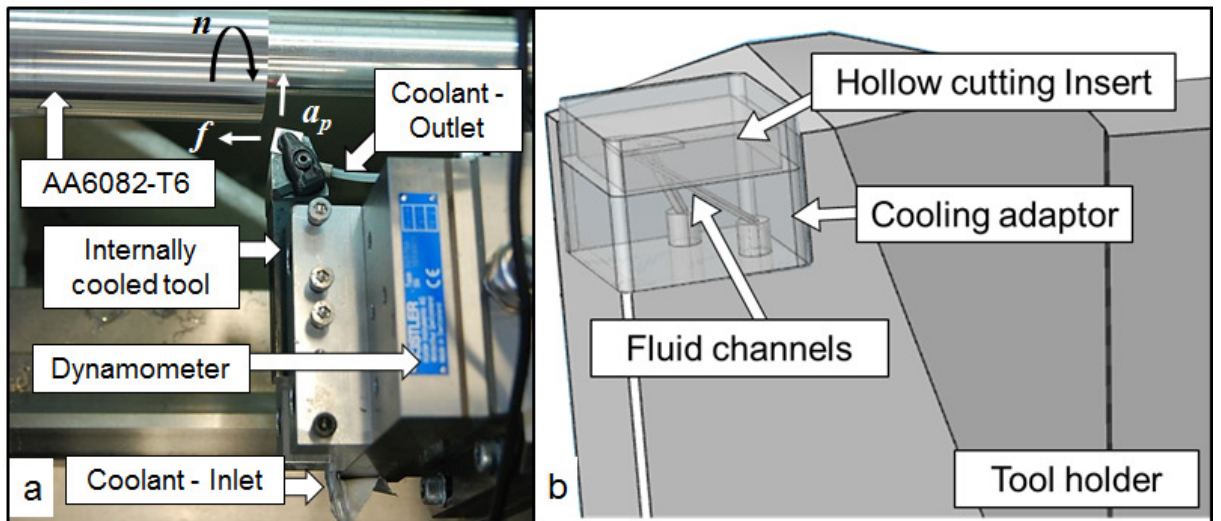


Figure 1: (a) The experimental set-up for the cutting trials. (b) A 3-D model of the assembled internally cooled tool system.

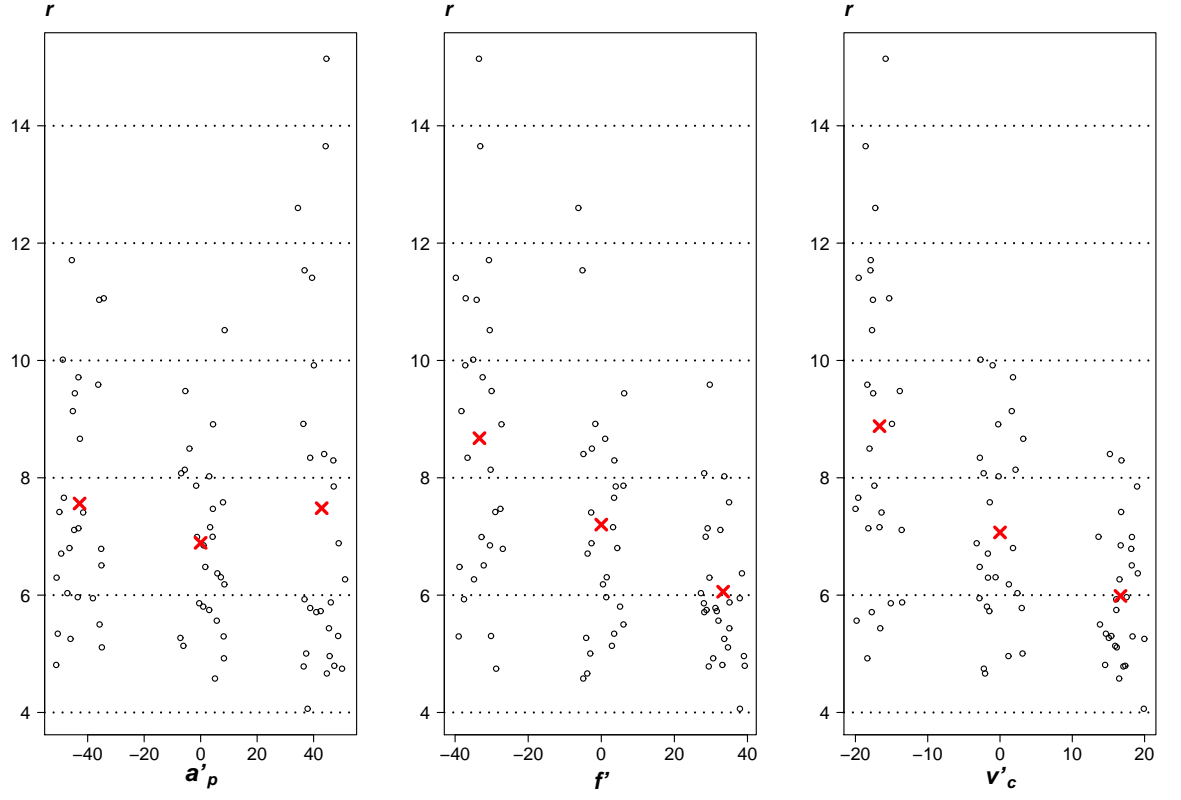


Figure 2: The ratio  $r$  versus the dimensionless technological variables  $a'_p$ ,  $f'$  and  $v'_c$ . The abscissae have been jittered. The cross designates the sample mean for each of the three groups of data in each panel.

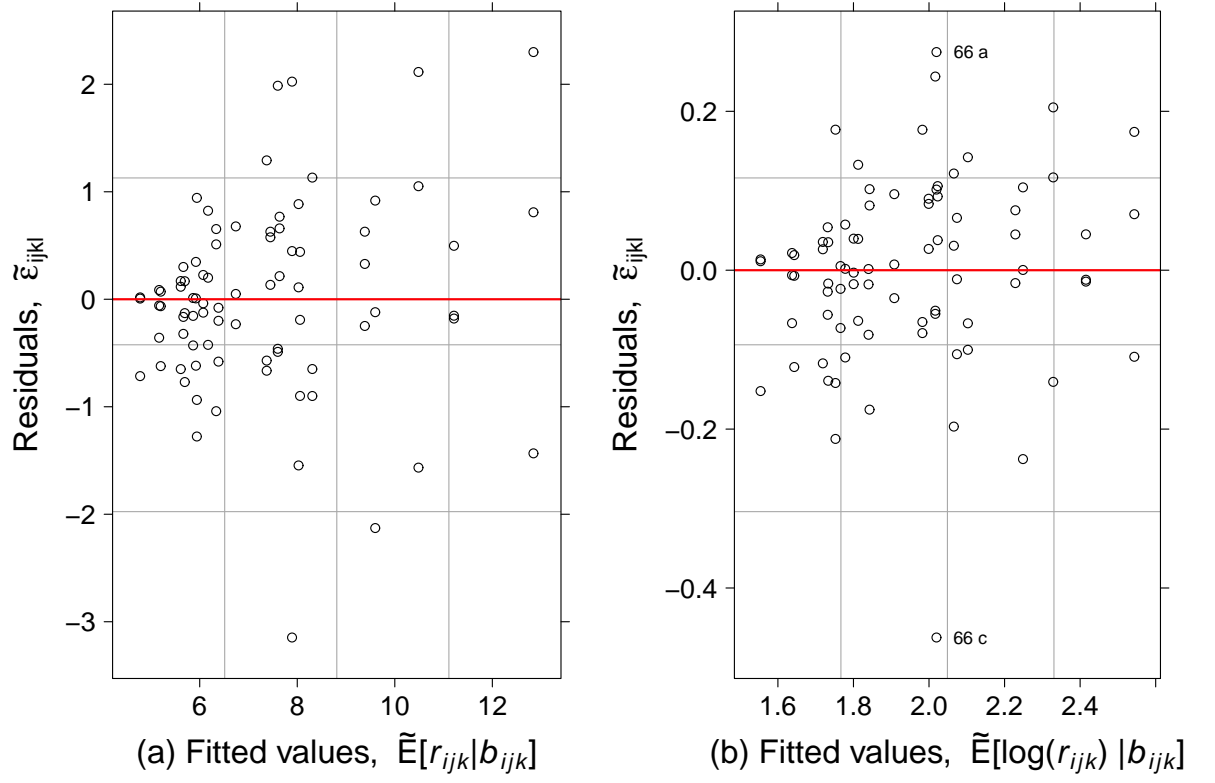


Figure 3: Residuals versus fitted values (alias predicted values) (a) of the simplified model (Equation (7)) (b) of the log-transformed simplified model (Equation 8 or 9).



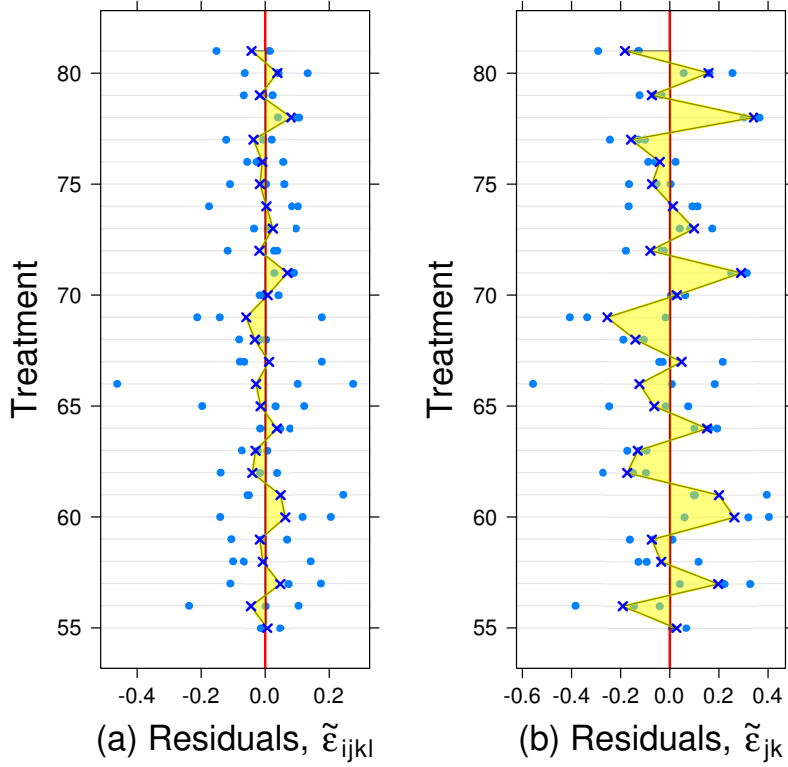


Figure 4: The realisations of the non-observable residuals versus the values fitted by (a) the model that includes the random effects (Equation 8) (b) the model that does not include the random effects (Equation 10). The average for each treatment is identified by the points 'X'. The shadow area underlying the segments joining these averages facilitate the visualisation of the different amount of violation of the assumed zero mean for errors of the two models.

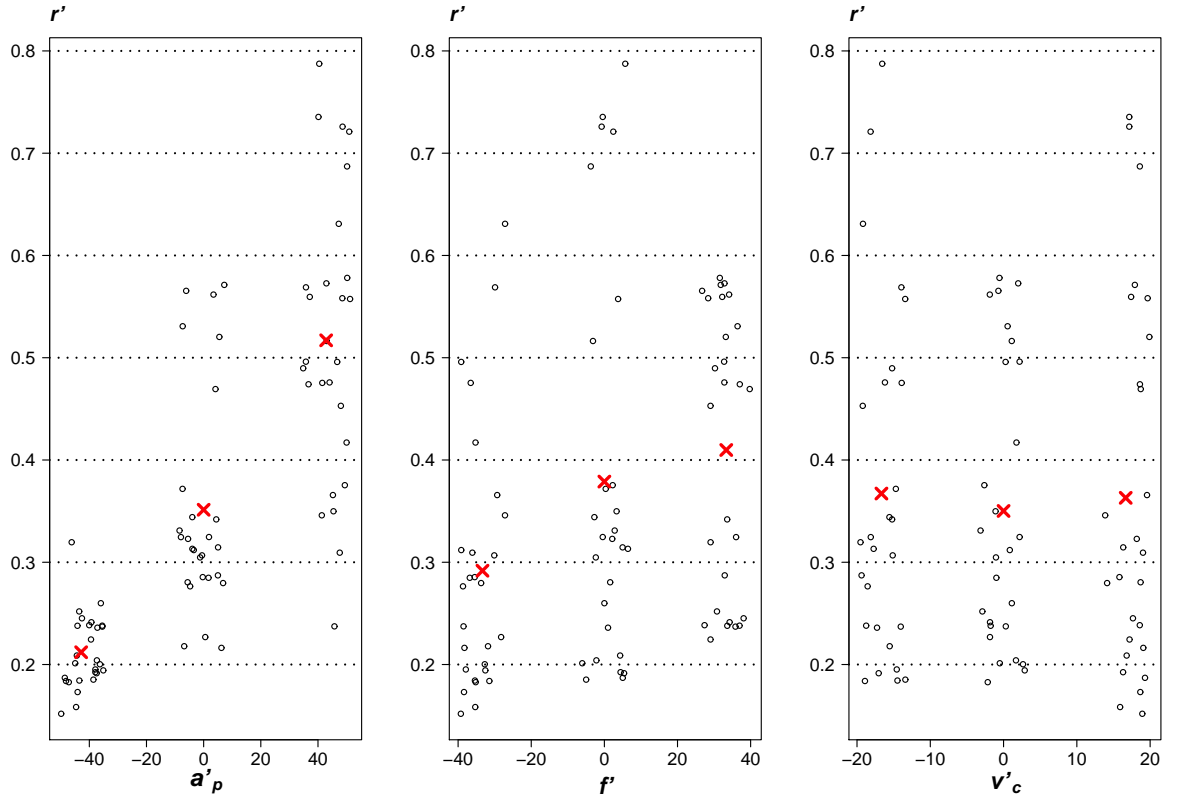


Figure 5: The ratio  $r'$  versus the dimensionless technological variables  $a'_p$ ,  $f'$  and  $v'_c$ . The abscissae have been jittered. The cross designates the sample mean for each of the three groups of data in each panel.

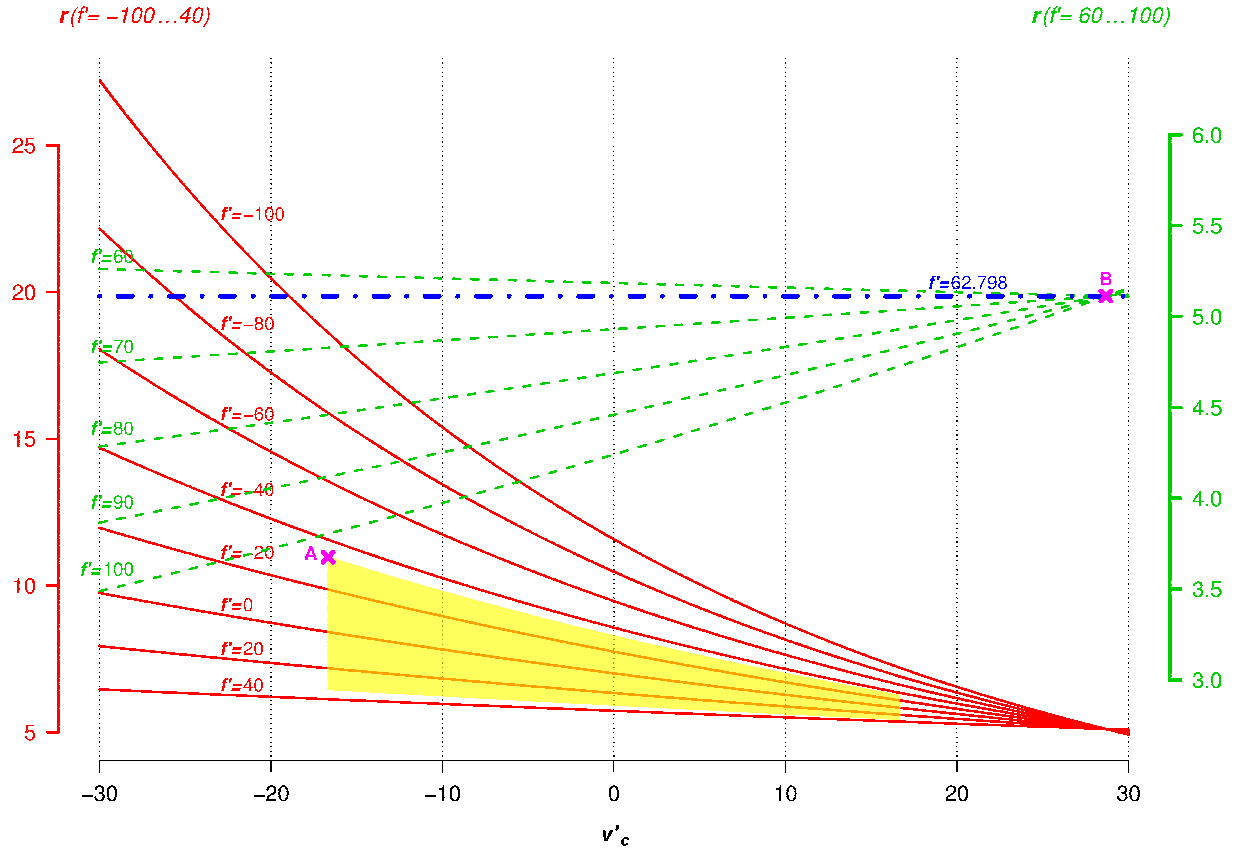


Figure 6: The expected value of the efficiency ratio  $r$  versus the dimensionless cutting speed  $v'_c$  for selected  $f'$  values ranging from -100 to 100. The highlighted area in yellow/light-grey in colour/black-and-white print represents the experimental region investigated. The point A identifies the maximum efficiency in that area. The point B identifies the stationary saddle point. The thicker dotted and dashed line is horizontal (iso-efficient line).

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Table 1: Technological variables and their values.

Variable	Unit	values
depth of cut, $a_p$	mm	0.20, 0.35 and 0.50
feed rate, $f$	mm/rev	0.10, 0.15 and 0.20
cutting speed, $v_c$	m/min	250, 300 and 350

	numDF	denDF	F-value	p-value
(Intercept)	1	54	995.5	<0.0001
$a'_p$	1	19	0.01980	0.8896
$f'$	1	19	21.25	0.0002
$v'_c$	1	19	25.99	0.0001
$a'_p f'$	1	19	0.3581	0.5566
$a'_p v'_c$	1	19	0.1678	0.6866
$f' v'_c$	1	19	7.753	0.0118
$a'_p f' v'_c$	1	19	2.1257	0.1612

Table 2: Sequential tests of the hypotheses for the significance of the independent variables and their interactions both listed in the first column. ‘numDF’ and ‘denDF’ are the numerator and denominator degrees of freedom, respectively. The p-values are expressed in fractions of the unity rather than in per cent.

Parameter	ML estimate	standard error
$\beta_0$	1.947	0.03105
$\beta_2$	-0.005020	0.001141
$\beta_3$	-0.01099	0.002282
$\beta_6$	0.0001750	0.00008384
$\sigma_b$	0.1378	
$\sigma$	0.1316	

Table 3: ML estimates of the parameters for the model with Equation 8 or 9. For the estimators of the  $\beta$ 's the standard errors are also shown.

Parameter	ML estimate	standard error
$\beta_0$	-1.116	0.03329
$\beta_1$	0.01012	0.0009513
$\beta_2$	0.005377	0.001223
$\sigma_b$	0.1518	
$\sigma$	0.1316	

Table 4: ML estimates of the parameters for the model with Equation 11. For the estimators of the  $\beta$ 's the standard errors are also shown.